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The extraordinary universe of Peter Apian: technical investigation of five copies of a 16th-century astronomical book

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Abstract
In 1540, in Ingolstadt, Germany, the influential astronomer and printer Peter Apian produced the *Astronomicum Caesareum*: a printed and hand-coloured astronomical book visualising the Ptolemaic universe through the use of diagrams and wheelcharts, worthy of his imperial patron, Charles V. About 130 copies have survived to this day, with varying degrees of paper quality and level of decoration, and only eleven volumes are considered deluxe copies. We thoroughly analysed one deluxe volume held at the Fitzwilliam Museum, Cambridge, and compared the results with four (one deluxe and three standard) other copies from institutions in the UK. A non-invasive analytical protocol was applied, including extensive microscopy, fibre-optic reflectance spectroscopy (FORS), X-ray spectroscopy (XRF), macroscale XRF (MA-XRF) and Raman spectroscopy. The most interesting pages were chosen based on art-historical evidence and the variety of the colour palette, including on volvelles (wheelcharts) and coats of arms. Following a systematic approach, we analysed the same pages in each volume, gathering information on the colour palette in all the volumes. The type of paper and the presence of watermarks were also documented. A wide range of materials was identified in the five copies, including red, purple and yellow organic dyes, lead white, verdigris, vermilion, azurite, indigo, smalt, and lead–tin yellow. Mosaic gold was used to embellish certain paint passages in the deluxe volumes and metals (gold and silver) were applied on some pages. The comprehensive findings were essential to identify specific traits related to Apian's workshop, to differentiate deluxe from standard copies, to suggest an order of production of the copies, and to provide new information on this landmark book and more generally in an under-researched field of study.

Keywords Peter Apian, *Astronomicum Caesareum*, Printed book, Sixteenth century, Germany, Non-invasive analysis, Watermarks, FORS, MA-XRF, Raman

Introduction

Non-invasive scientific methods for the analysis of pigments and painting techniques have been extensively applied to medieval manuscripts [1–3], but only a very limited number of studies have been published on early printed books from the 15th [2, 4, 5] and 16th [6–9] to the 18th century [9]. More generally, recent scholarship on early printing has begun to apply methodologies broadly adapted from manuscript studies (for illumination see [10, 11], in particular the examination of copy-specific features that distinguish individual volumes within a printed edition [12, 13]. New findings from hand-painted prints in pre-modern Europe have most prominently been presented in the exhibition at the Baltimore Museum of Art and subsequent publication edited by Susan Dackerman [14, 15].

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Within this relatively young sub-field in the history of printing and the study of book arts, the current project has taken a focused approach and considered the materials and techniques deployed in selected copies within a single prestigious production by one workshop, that of Peter Apian (1495–1552).

Peter Apian—mathematician, cartographer, astronomer, and printer—was extremely influential during his lifetime. He studied under Georg Tannstetter in Vienna before joining the university in Ingolstadt (Bavaria), where he set up a print workshop, printing a range of texts from popular treatises on commercial arithmetic to practical astronomical treatises in the vernacular and cosmographical works which were used as textbooks at universities across Europe. He wrote and, in 1524, printed the first edition of his *Liber Cosmographicus,* a textbook on cosmography, cartography, and other topics, which included diagrams and volvelles. Over 30 expanded editions were published in the sixteenth century and fourteen different translations were made. It was this publication which made him known to the Holy Roman Emperor Charles V and afforded him the patronage necessary to produce his most visually, technically, and intellectually impressive work, the *Astronomicum Caesareum* (AC) [16]. This was designed with the help of two artists [17] and is one of the finest and most elaborate early modern scientific books. Printed in 1540 for his Imperial patron, Charles V, the book contains some thirty movable wheelcharts (or volvelles), with varying degrees of decoration and grandeur, aiding the calculation of the longitude and latitude of the planets in their movement around the central earth [18, 19]. Visualising a Ptoleomaic universe, and published only three years before Copernicus's *De revolutionibus,* his book provides modern audiences with insights into a pre-Copernican cosmic imagination. Charles rewarded Apian's achievement by knighting him in 1541, and the consequent change of his coat of arms at the end of the AC allows us to date individual copies to before and after 1541.

While the scientific innovation and functions of Apian's paper instruments and the role of this book in the development of interactive print technologies has been studied [20, 21], little work has been carried out on the creation and production of the illustrations themselves. Approximately 130 copies of this volume are extant today. While all were printed, coloured and mounted in Apian's own workshop in Ingolstadt[1], the quality of the paper and the level of decorative detail vary significantly from copy to copy. Of the extant corpus of AC as outlined by Gingerich, eleven volumes are deluxe copies, probably destined for presentation. A presentation copy is defined as a book that we know was offered to significant people by an author—in this case, copies of the AC that are linked to the libraries and networks of Apian's patrons and benefactors. Gingerich argued that presentation copies are set apart from standard copies by the choice of paper. However, our study suggests that a broader range of criteria needs to be considered and there is ambiguity as to whether 'deluxe' and 'presentation' are synonymous.

In the current investigation, one deluxe presentation copy of the book held at the Fitzwilliam Museum has been subjected to a deep non-invasive investigation to understand the materials employed and the painting technique. In addition, four other copies preserved in different collections in the UK were analysed in situ, taking the first step towards an understanding of Apian's workshop processes and defining the order of production of the books.

The non-invasive analytical protocol was carried out in the scientific laboratory of the Fitzwilliam Museum, and adapted for off-site work when the books could not be transported. The first step was the examination of the folios, in normal and raking visible light. The latter was useful to understand the surface texture and marks of bearer type (the blind impressions of printing blocks or pieces of type used to regulate the pressure of the press when printing pages with large blank areas), and marginal notes added to early printings of the work. Transmitted light, with a light-sheet positioned underneath the folio, was used to document the watermarks. Close observation under the microscope was then considered essential to magnify the details and better understand the pigment particles, if present. A range of spectroscopic techniques was employed next; in particular, fibre-optic reflectance spectroscopy (FORS) in the UV–visible-NIR range and X-ray fluorescence spectroscopy (XRF). FORS was carried out on all the main coloured areas of the folios to identify a large number of pigments, whereas XRF was used in order to narrow down the presence of some pigments, characterise possible impurities, and detect metals. On the volume held at the Fitzwilliam Museum, macroscale XRF (MA-XRF) scanning and Raman microspectroscopy were also carried out. MA-XRF was employed on two volvelles to help visualise the distribution of specific chemical elements, and Raman microspectroscopy was used to confirm the presence of some pigments and thus refine the results. The combination of these methods allows us to identify the pigments and paint binders and to understand the painting technique; moreover, they are complementary because they

[1] This statement is confirmed by the fact that the New College copy has printed and coloured volvelle remnants on the *back* of another volvelle wheel, the use of the blank side of an otherwise defective sheet, which would presumably otherwise have been put for waste, preserving evidence that the colouring was carried out in the printing workshop rather than after the completed book had left the printer.

Table 1 Description of the five copies studied

Collection and shelfmark	Papers	Text on G4r	Insignia, last page
Fitzwilliam Museum (FM), Cambridge* PB 18–2020	Main text paper is uniform heavy stock, volvelles are printed on a mixture of papers of lighter weight	No text	Small coat of arms
National Library of Scotland (NLS), Edinburgh* Newb.4968	Printed on a mixture of papers of lighter weight	Text on separate pieces of paper pasted on to the leaf	Large coat of arms
Peterhouse College (PC), Cambridge S.9	Printed on a mixture of papers of lighter weight	Included in the text block and printed on same sheet as volvelle base	Large coat of arms
New College (NC), Oxford BT1.70.2	Printed on a mixture of papers of lighter weight	Included in the text block and printed on same sheet as volvelle base	Large coat of arms
British Library (BL), London Maps C.6.d.5	Printed on a mixture of papers of lighter weight	Included in the text block and printed on same sheet as volvelle base	Large coat of arms

Volumes marked with an asterisk are presentation copies

work at different scales and perform better in the analysis of different ranges of materials.

The investigation followed a systematic approach, exploring several coloured areas in the chosen folios, then focusing especially on the similarities and differences among the volumes in terms of the blue pigments used, the presence of metals (gold and silver), and the use of yellow pigments for specific purposes and decoration.

A comprehensive knowledge of the materials of an object is essential to identifying specific traits related to an artist or their workshop, and the present study offers new ways of understanding the production of this landmark book. Furthermore, by comparing the results from the five books, we are able to suggest an order of production of the copies, providing novel information in an under-researched field of study.

Materials and methods

Materials

All copies of the AC in the UK in public collections and one in a private collection were surveyed. A selected corpus of five copies of the AC was investigated in depth, all printed in Ingolstadt from 1540. The Fitzwilliam Museum (FM) and National Library of Scotland (NLS) volumes, printed on heavy stock and lighter stock respectively, are presentation copies with characteristics of the deluxe production. The FM volume was given as a presentation copy to Oswald von Eck (1524–1573) (son of the Bavarian chancellor Leonhard von Eck), who wrote his name in brown ink on the first page. The NLS volume was probably owned by Wilhelm IV or Ludwig X, the co-regent Dukes of Bavaria, and when Wilhelm's son, Albrecht V (1528–1579), inherited the two copies owned by his father and uncle, he kept one copy in his library while the second, the volume now in the National Library of Scotland and studied in this paper, was gifted to Wolfgang Bosch, Mayor of Ljubljana, Slovenia, in 1541 (it has an armorial dedication page with Albrecht's coat of arms added to the front pastedown). The other three copies are printed on the mixed lighter paper stocks of the standard production (Table 1, Fig. 1, Figure S-1).

Methods

FORS spectra were acquired in the 350–2500 nm range using a FieldSpec4 fibre optic spectroradiometer (ASD Inc., part of Malvern Panalytical) with integrated light source and a bifurcated fibre-optic probe. The instrument's resolution is 3 nm at 700 nm, and 10 nm at 1400 and 2100 nm, and the wavelength accuracy is 0.5 nm. The probe was usually hand-held above the area to be analysed at a 90° angle and at a distance of about 5 mm. Analysed areas were illuminated using ASD's Hi-Brite probe (halogen bulb, 2901 K colour temperature). The spectrometer was calibrated against a white Spectralon® standard. Spectra were collected and processed using ASD's RS3 and ViewSpec Pro software. Each spectrum was the result of 64 accumulations and took approximately 8 s to collect.

Several areas and details were examined and imaged using a Leica M80 microscope with integrated digital camera and magnification ranging from 7.5× to 60× and equipped with LED illumination. Images were recorded using the Leica Application Suite (LAS 4.13). When working off site, a Dino-Lite Edge AM7915MZTL was employed, with long working distance, 5 Megapixel sensor and magnification ranging from 10× to 140×. A Leica S8APO microscope was in use at the National Library of Scotland. The objective used is 0.32× and the zoom range is from 10× to 80×.

A Bruker ARTAX micro-XRF spectrometer with a rhodium anode was used for the analyses of the FM and PC books. The X-ray tube was operated either at 50 kV and

Fig. 1 Examples of A1r from **a** the FM presentation copy (© The Fitzwilliam Museum, University of Cambridge), and **b** the PC standard copy (image reproduced by kind permission of The Master and Fellows of Peterhouse, Cambridge). All images are available in the Supplementary Information

600 μA, or at 15 kV and 1100 μA with a Helium flush to aid the detection of light elements. The area analysed is typically of 650 μm in diameter. The measurements typically lasted 200 s each and were performed with no filters. Spectra were recorded and processed using the instrument's own ARTAX software. When working off-site, a portable Bruker ELIO was employed. This uses a rhodium target and can operate at < 50 kV and 80 μA, irradiating a sample area of ca. 1 mm diameter. Spectra were typically recorded over 60 s. Spectral images were exported as .bcf files and processed using the ESPRIT Reveal software by Bruker.

A M6 Jetstream (Bruker) X-ray fluorescence spectrometer with a rhodium anode and polycapillary optics was used to scan two volvelles (B3r and H1r) of the FM book. The X-ray tube was operated at 50 kV and 600 μA under ambient conditions with both 60 mm^2 SDD detectors in operation with a 275 kcps detection threshold. The scan was performed with a 10 ms dwell time at each pixel, a 220 μm beam size, and a pixel step size of 250 μm.

A fibre-based, transportable spectrometer (iRaman Plus, B&W Tek) was used for Raman analysis, equipped with a laser diode operating at 785 nm and spectral resolution of 3 cm^{-1}. Laser power at the sample was used in the range 3–10 mW, with the laser spot on the sample estimated to be ca. 90 μm diameter. A portable microscope with a 40 × objective was attached to the instrument to facilitate positioning and focusing of the measuring head over the area under analysis, which measures a few microns in diameter.

Transmitted visible light images of the watermarks were collected using a CXD Light Sheet A3 (41.5 × 31.3 cm) with 0.5 mm thickness; the lit area is 40.1 × 30.1 cm. Watermarks were traced from the book with a 2B pencil onto archival silicone release paper, then scanned with the scalebar added.

Results

Materials characterisation of the FM volume

Several coloured areas were investigated in the five copies. The pages were selected on the basis of their historical interest (for example, the universe painted on B3r and the volvelles depicting dragons of F3r and G3v) and the presence of a wide range of colours. The selection,

Table 2 Summary of the pigments identified in the five copies of the *Astronomicum Caesareum*

	Pigments	FM	NLS	PC	NC	BL
Blue	Azurite	√	√	√	√	√
	Indigo	√	√	√	√	√
	Smalt				√	√
Green	Verdigris	√	√	√	√	√
Yellow	Yellow organic dye	√	√	√	√	√
	Lead–tin yellow	√	√			
	Mosaic gold	√	√			
Red and pink	Red organic dyes (brazilwood)	√	√	√	√	√
	Vermilion	√	√	√	√	√
	Red organic dye + vermilion	√	√	√	√	√
Purple	Purple dyes (folium)	√	√	√	√	√
White	Lead white	√	√			
	Paper	√	√	√	√	√
Metals	Gold	√				
	Silver	√				

repeated in each volume, included the initial page and its verso (A1r, A1v), containing the coats of arms of the patrons, nine pages with volvelles (B3r, D3r, F1r, F3r, G3v, G4r, H1r, I2r, M3r), and the final page with the insignia of Peter Apian (O6r). As contemporary illuminators had different materials, in particular blues, available at a range of quality and price, we also analysed any blue areas throughout each volume in order to characterise the blue pigments, the choice of which is a useful indication of the status of a particular volume.

This section focuses on the results obtained on the FM volume, describing all the pigments, colourants and metals identified. The results from all the analysed copies are summarised in Table 2.

White areas are usually left unpainted, but lead white, suggested by the detection of Pb in XRF, can be found in several mixtures to lighten the hue, and is sporadically used as white pigment (Figure S-2).

Green passages contain a copper-based green pigment, most likely to be verdigris, due to the presence of Cu in the XRF spectra and the apparent absorbance maximum around 720 nm in the FORS spectra [22] (Figure S-3). This is confirmed by the absence of other bands in the NIR region that are associated with sulphates, chlorides or carbonates [23] and related elements detected by XRF. Various shades of green are present in the book, and yellow organic dyes were probably added to modify the hue. Lipids, associated with an egg yolk or oil binder, were identified on almost every green area analysed by the absorptions at 2310 and 2350 nm in the FORS spectra [24].

The mineral pigment azurite, detected by the absorption bands at 640, 2285, 2350 nm in the FORS spectra and containing mostly zinc impurities found by XRF, is the preferred pigment for blue areas, including the coats of arms. Plant-derived indigo (or more likely woad), characterised by the FORS absorption band at 660 nm, is used to paint lighter blue areas instead (Figure S-4).

The wide range of red and pink hues is achieved with red organic dyes, diluted in various proportions or mixed with other pigments to represent the large number of shades. Red areas are usually painted with red organic dyes. They are often very diluted, but in some areas the log 1/R coordinates show a broad peak at 555 nm, similar to that of brazilwood (*Caesalpinia* plants) (Fig. 2a). Vermilion was detected in small details by Raman (peaks at 250 and 340 cm^{-1}), such as some of the constellations and on all the flesh tones of B3r, as evidenced by the MA-XRF map. Pink areas contain diluted red organic dyes, while purple areas are painted with purple dyes, possibly the plant-based folium (*Chrozophora tinctoria*), as shown by the log 1/R FORS spectra with peaks at 545 and 580 nm (Fig. 2b). A characteristic salmon pink is often identified in various volvelles: it is painted with a mixture of a pink dye and a small amount of vermilion (Figure S-5).

Lighter and darker shades of yellow are achieved with what looks like a yellow dye under the microscope; however, FORS spectra were inconclusive for the characterisation of the colourant (Figure S-6). Lead–tin yellow type I was found only on H1r, and identified by the Raman peaks at 127 and 193 cm^{-1} (Figure S-7); the overlapping of Pb and Sn can be visualised in the MA-XRF map (Fig. 3).

Yellow sparkling particles appear on some colours throughout the book, often on yellow and salmon-pink areas. Under the microscope, they look like golden

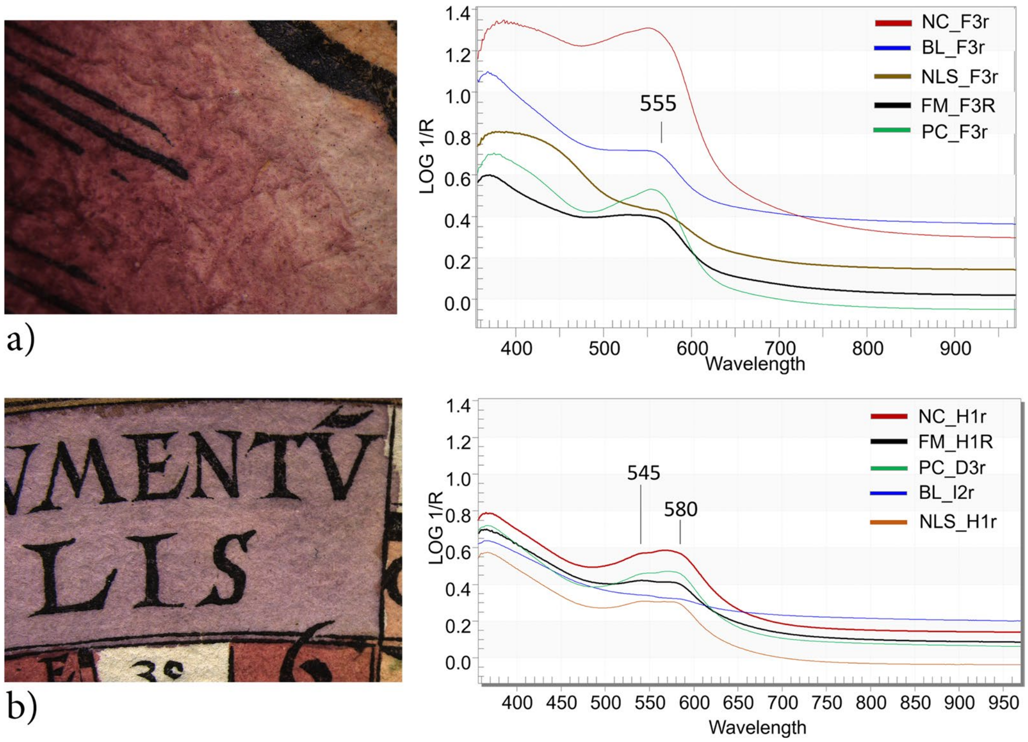

Fig. 2 FORS spectra collected on pink and purple dyes on the five copies: **a** pink dye (image from page F3r, NLS copy) and FORS spectra showing a peak at 555 nm, associated with brazilwood; **b** purple dye (image from page H1r, NLS copy), FORS spectra showing peaks at 545 and 580 nm, possibly related to folium

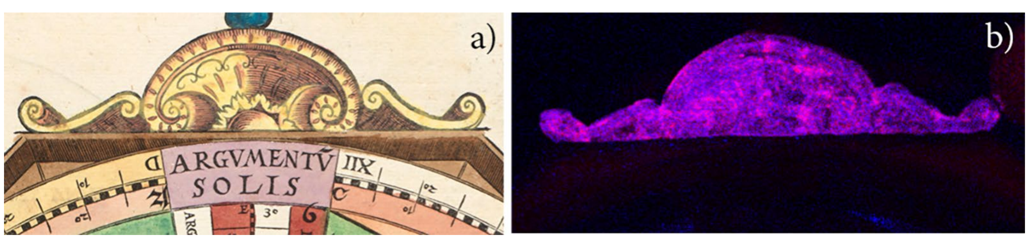

Fig. 3 MA-XRF distribution maps of Pb and Sn on H1r. The presence of lead–tin yellow is evidenced by the purple hue obtained by the false colour maps of lead (in red) and tin (in blue)

particles that sparkle under normal light. The Raman peak at 314 cm^{-1} identifies mosaic gold (tin sulphide) [25] (Fig. 4). The identification of mosaic gold on manuscript illuminations [26, 27] as well as on 15th-century printed books of German origin [28] is attested, corroborating the result.

Gold, identified by XRF, was used to paint the dotted stars and the boxes outlining the names of the constellations on B3r, as clearly evidenced by the gold (Au-Lα) distribution map (Fig. 5b). Silver, now tarnished, is instead detected on some other details on B3r (stars, swords and armour) (Fig. 5b) and to a lesser extent on F3r (on the dragon's eyes, horns and veining of the wings).

Characterisation of materials in the other four volumes

The NLS presentation copy shows many similarities with the FM volume. The wide range of red and yellow organic dyes and the use of verdigris, lead white, vermilion, and indigo are applied in a manner comparable to the FM presentation copy. Similarly, lead–tin yellow is detected only on H1r, while mosaic gold is applied to embellish certain colours throughout the book (Figure S-8). Azurite is the preferred blue pigment, but the prevalence of titanium and zinc impurities could indicate the use of a different pigment batch than the one used for the FM copy, which contained mostly zinc-based impurities. Titanium and zinc impurities are

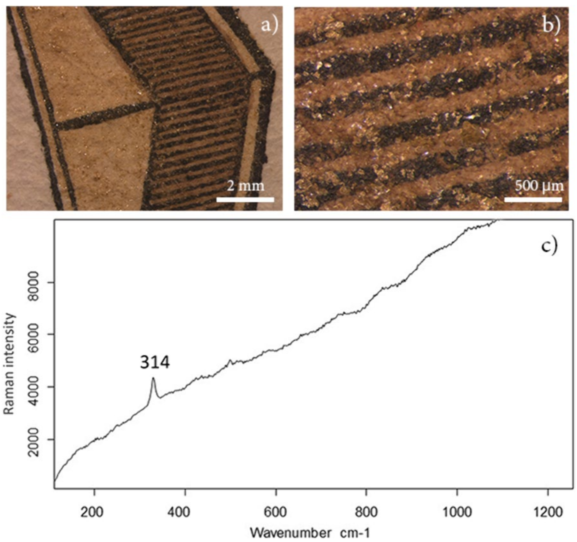

Fig. 4 **a**, **b** Details of FM M3r under the microscope at different magnifications, showing the presence of glittering particles; **c** Raman spectrum collected from a particle, the peak at 314 cm^{-1} is associated with mosaic gold

often found in natural azurite [29, 30]. Gold and silver are also detected in the NLS copy. However, these metals are not applied within the volvelles but only associated with external details: silver is applied on the leather finding tabs and gold on the gilded edges.

The three standard copies analysed show a reduced palette and a limited variety of shades for organic dyes. Moreover, indigo is the preferred blue pigment for these volumes, in which azurite was sporadically detected only in small details and only on specific pages. A third blue pigment is found only on the British Library (BL) and New College, Oxford (NC) books: smalt, a glass containing cobalt, was found by FORS [22] on G4r in both copies, as well as in several areas painted at the top of the volvelles of the BL copy. Based on the XRF results, several impurities were detected, such as arsenic, nickel, bismuth, and iron [31–33]. Moreover, in the BL copy, smalt often appears pale grey instead of the usual bright blue: this may be due to a degradation process possibly linked to a different binder used in those areas [34, 35] (Fig. 6).

Papers

Deluxe and standard copies of the AC have usually been distinguished on the basis of the paper stocks used for the leaves. However, an exception is the Edinburgh presentation copy, which has the colouring of a deluxe copy despite having all the signs of being a later state of the work, printed on lighter-weight paper. A high-quality, heavy, Imperial-size paper (520 mm x 750 mm) ([36] no. 2125) with a pinecone watermark (not, as Gingerich describes it, a cluster of grapes: [37]), identified in the Bernstein index with the coat of arms of Augsburg, is used for deluxe copies. Despite water- and insect-damage which probably occurred before the beginning of the nineteenth century, this paper stock in the FM copy still preserves the characteristic marks of the rope over which the newly made sheets were hung to dry in many of the spine margins, indicating that the leaves were not been beaten before binding or pressed during later rebinding. Rope-marks are also visible in the Peterhouse copy. The leaves of the standard copies are of a thinner paper taken from various stocks, mixtures of the stocks being used in each copy. The watermarks found in the leaves of standard copies studied are: a tower surmounted by a crown and a flower; a triangle and flower; and an armorial eagle. All the watermarks identified in the five books can be found in the Supplementary Information (Table S-1).

The volvelles for all copies studied are printed on lighter-weight paper, apparently of a smaller size (between about 300 and 320 mm × 430–440 mm, according to those measurements which have been published, although not all sizes are recorded) ([36] nos. 1113; 2174;

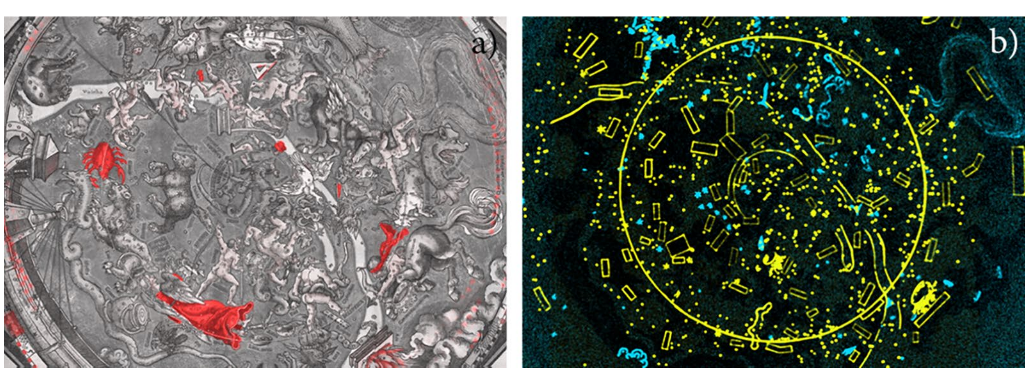

Fig. 5 **a** MA-XRF distribution map for mercury (red) overlayed on the black and white image of FM B3r; **b** MA-XRF distribution maps of gold (yellow) and silver (light blue) of FM B3r

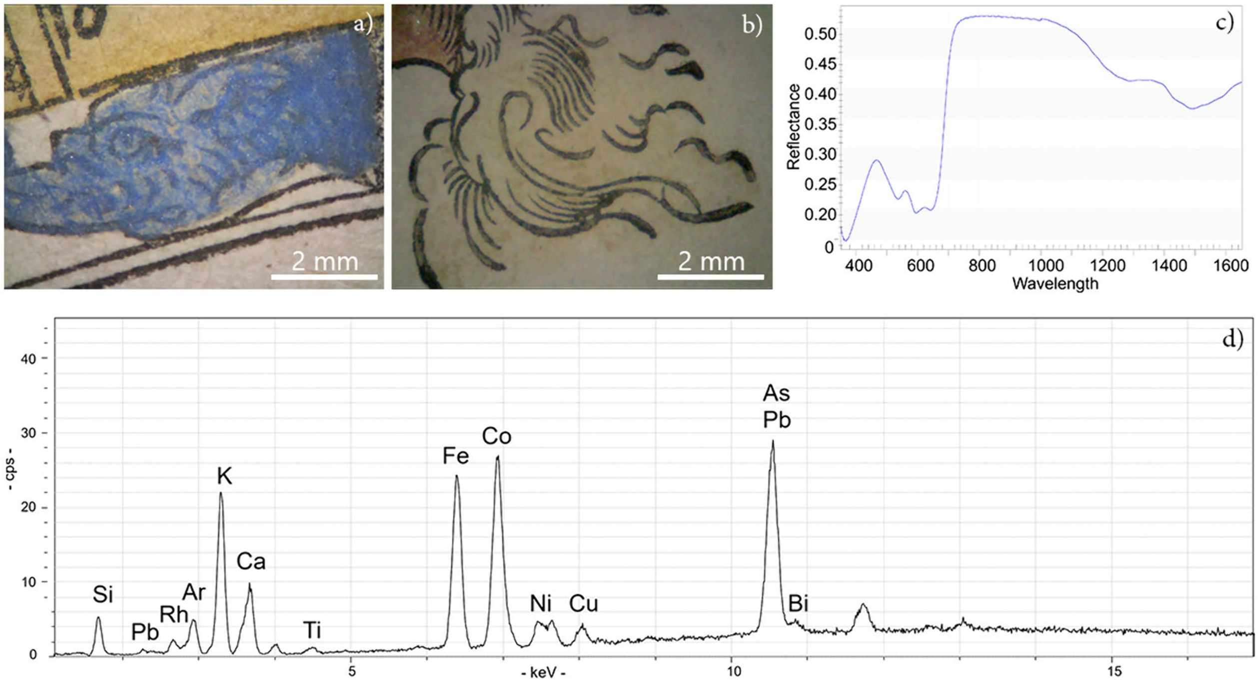

Fig. 6 Analysis of the smalt on the BL book: **a** detail showing the blue colour of G4r; **b** detail showing discoloured smalt on G5r; **c** FORS spectrum and **d** XRF spectrum collected on the blue area of (**a**). Images reproduced by kind permission of the BL

8771, 8791, 8795, 8697; and 12,307, 12,308) and share a different set of watermarks, some of which are difficult to record fully due to being obscured by other wheels on top of them. Six watermarks were found in the volvelles: a salt-cellar in a shield; a crown supporting a tall gothic arch surmounted by a cross and a star; a bear; three hats with ties in a shield, identified in the Bernstein portal, The Memory of Paper [38], with the Arms of Landshut; a letter, possibly ‘p’; and a different letter, probably ‘p’ with a star in a shield. (The last watermark was the most difficult to read in the volumes studied due to its position in the volvelle wheels.) Within the volvelle on a single leaf, different watermarks can be found in different wheels. Lighter-weight, that is to say thinner, papers were used for the wheels of the volvelles to minimise the bulking out of the leaves in the bound book. Nevertheless, the additional thickness in the centre of the leaves makes the AC a difficult book to bind, as the spine is so much thinner than the thickest area of the textblock. Thread impressions in the FM copy indicate that the book was sewn with a heavy thread/thin twine with a fairly tight twist, presumably to create enough swell in the spine to prevent the sewing structure from collapsing and to allow the spine to be shaped appropriately.

Discussion: painting technique and order of production

When considering the production of this corpus it is useful to think of the individual books as states bearing witness to different moments in the production of the work. The basic pattern of production—printing and hand-colouring of the complete work (text and volvelles), followed by cutting out and assembly of the volvelles—is complicated by evidence of ideas developing in the mind of the author-printer as production progressed. Indeed, he seems to have implemented two changes which can be used to organise the volumes by order of production. The first is the addition of printed marginal notes on G4r. This text, which is completely missing in the FM copy, is present in the NLS copy in the form of printed pieces of paper pasted on to the page, and in the BL, PC and NC copies, is printed directly on to the page (Table 1, Figure S-9), strongly suggesting that Apian realised the need for these notes after production had begun, then incorporated them first as physical additions, then as integral parts of the printed text. In addition, blind impressions in the margin of D2v of the FM copy are the result of adding a marginal note on D3v, the sheet being put through the press a second time to add extra information, after it had been folded ready for binding. The second relates to Apian's own change of status, demonstrated by the two forms of insignia (initially a modest roundel, but superseded by an elaborate full-page armorial achievement after he was knighted) on the final page of the book (Figure S-10).

Close study of the printed pages under a microscope shows that some pages are more important than others—the celestial map (B3r), the dedicatory coat of arms opening the book (A1r), and the dragon volvelles which operate as an emblem (F3r and G3v)—demonstrating internal hierarchy of volvelles within the book itself. This is demonstrated by the use of azurite (rather than cheaper indigo), more expensive materials such as gold and silver, and a more careful application of pigments and shading (Figure S-11).

The use of blue pigments deserves further explanation, because a production pattern can be discerned in their application. As outlined above, blue is usually rendered using either azurite or the plant-based indigo (probably woad), and occasionally also smalt (Table S-2). Azurite is the preferred pigment in the two presentation copies, while indigo is used as the default blue in the other volumes. However, the presence of the two pigments appears to follow a pattern, in which the same pages and details of different volumes contain either azurite or indigo. This suggests that the books were produced in batches and the labour divided between different members of the workshop. The base leaves would have been coloured in groups using the same materials (either azurite or indigo), and the various dials of each volvelle were also coloured using a similar process, rather than a single volvelle, of multiple dials, being produced as a standalone object. In other words, several identical volvelle dials were painted at the same time. The choice of using smalt on the BL volume, and on one volvelle of the NC copy, also points to this workshop practice and could suggest that this pigment entered Apian's palette at a later point, because both volumes were produced towards the end of the production history.

Across the corpus, colours do not indicate a particular function or use within the volvelles, as they vary in the same volvelle across the different books. The difference in colour makes the interactive diagrams easier to read and use, but the colours used do not, in standard copies, have an inherent meaning [39]. However, in presentation copies there is more standardisation across the corpus, indicating that some colours may have been used with semantic intent. For example, lead–tin yellow is used in presentation copies in the volvelle of I2r, which relates to the sun. This is a more expensive and prestigious pigment than the yellow dye commonly used on every other page and originates from a medieval alchemical tradition in which it was used to depict gold [40, 41].

Conclusion

Non-invasive analysis of the five hand-coloured printed books has provided evidence for the identification of pigments and colourants, metals and binders, shedding new light on the materials and techniques of this type of object printed in sixteenth-century Germany.

A wide range of materials, including red, purple and yellow organic dyes, lead white, verdigris, vermilion, azurite, indigo, and smalt, was identified in the five copies of the *Astronomicum Caesareum* printed and hand-painted by Peter Apian's workshop. Differences between deluxe and standard copies are highlighted by a wider range of materials in the former: in particular, an extensive range of colourants obtained through dilutions and mixtures with other pigments, the use of gold and silver, the choice of employing lead–tin yellow type I on the volvelle of H1r, the application of mosaic gold to embellish some colours throughout the volume, and a more precise application of colours within the printed lines. In the context of the Edinburgh copy, which has a printed armorial dedication and is therefore a presentation copy, this finding complicates our understanding of the edition falling neatly into mutually exclusive categories of deluxe and standard copies, with deluxe volumes alone being used for presentation. The Edinburgh copy is on the lighter-weight 'standard' paper stock but has a range of pigments that overlaps with the Fitzwilliam copy, which is printed on the heavier-weight paper. Thus 'deluxe' and 'presentation' as descriptive terms are not entirely synonymous, and the paper stock alone cannot be taken as conclusive evidence for the status of a copy of the AC as deluxe.

The choice to use predominantly azurite in deluxe and presentation copies and indigo in standard copies underlines how the books were likely coloured in batches. In addition to this sign of assembly line production, we also found a more individual attention on especially significant volvelles, indicating not only the intensely collaborative nature of the production but also the close supervision of specific copies within it.

Based on two changes that occur within this corpus of five books (the addition of printed marginal notes on G4r; the change of insignia) we have suggested an order of production for the volumes, which will be helpful in placing other copies earlier or later in the overall production run. The presence of smalt may also indicate a possible later date for a particular copy, but further analysis of a broader set of objects is required to establish how widespread the use of this pigment was.

The characterisation of the materials used in the AC and the differences between presentation and non-presentation copies, the new insights gathered into the working practices of Apian's workshop, the choice of colours and pigments in certain priority volvelles, and the order of production of the five volumes, contribute new technical information to the limited studies currently published on this type of art, and provide essential details on an edition that was considered the high point of printing in the sixteenth century.

Supplementary Information

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Supplementary Material 1.

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Author contributions
SOS designed the study; FF performed the measurements and interpreted the results; EC carried out the study on the types of paper and watermarks. SOS, FF and EC wrote the paper. SR revised the paper, provided advice, and curated the bibliography in the introduction. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used for the Fitzwilliam Museum volume during the current study are available from the corresponding author on reasonable request. Data of the other copies are available from the authors upon reasonable request and with permission of the relative institutions.

Declarations

Ethics approval and consent to participate
Non applicable.

Competing interests
The authors declare that they have no competing interests.

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